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The Role of Microstructure in the Fast Fracture of Multipass Welds Deposited Using E-10018-M1 Electrodes

James L. Davidson

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ABSTRACT

Weld metal deposited using MIL-E-10018-M1 electrodes maintains very good fracture resistance, despite being comprised of a seemingly deleterious microstructure which includes extensive networks of pro-eutectoid grain boundary ferrite in the as-deposited weld metal and brittle martensite-austenite particles in the intercritically reheated weld metal and heat affected zone. To reconcile this contradictory structure-property relationship the report focuses on the fractography and metallography of a MIL-E-10018-M1 multipass weld, fractured during an explosion bulge test. Martensite-austenite particles identified in the intercritically reheated weld metal and heat affected zones were found to play no part in the fracture process. Pro-eutectoid grain boundary ferrite was shown to be the preferred fracture path in the as-deposited weld metal however, it does not substantially reduce the overall fracture resistance of the multipass weld metal. The very good fracture resistance of this weld metal is attributed to the interlocking grains of acicular ferrite contained within the prior-austenite grains and the relatively low volume fraction (18%) of as-deposited weld metal in the multipass weld.

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Executive Summary

A novel aspect of the COLLINS class submarines is that the forgings which form penetrations in the main pressure hull are made from a lower strength steel (HY590) than the hull structural steel (BIS 812 EMA). The shock resistance and safety of this feature was qualified, under AMRL supervision, by explosion bulge testing of panels made up of the two steels welded together with electrodes of an intermediate strength (E-10018-M1 electrodes). This weld metal exhibited an outstanding resistance to fracture under explosive loading.

During a survey of welds in the pressure hull of HMAS COLLINS, the forging-to-plate welds were found to contain a microstructural feature (pro-eutectoid ferrite along prior-austenite grain boundaries) which is generally believed to result in poor fracture resistance. This observation contrasted with DSTO's experience during the first article qualification of this weld metal by explosion bulge testing, during which, the same weld metal was found to have an outstanding resistance to fracture under explosive loading. An examination of the welds tested during the explosion bulge tests, verified that they also contained the deleterious microstructural feature and that they were representative of the weld metal in HMAS COLLINS. The significance of this observation is that because the weld metal tested in the explosion bulge tests maintained an outstanding resistance to fracture under explosive loading despite containing the supposedly deleterious microstructural feature, the weld metal in the HMAS COLLINS hull will also have an outstanding resistance to fracture under explosive loading.

The aim of this work was to reconcile the contradictory relationship between the outstanding fracture resistance demonstrated during the explosion bulge tests and the presence of a microstructural feature generally believed to result in poor fracture resistance. The report focuses on the examination of a forging-to-plate weld which was fractured during an explosion bulge test in order to determine if the supposedly deleterious microstructural feature played any part in the fracture process.

This report shows that the presence of the deleterious microstructural feature does not compromise the overall fracture resistance of the weld, because it occurs in isolated pockets of weld metal which account for only 18% of the total weld by volume. As a result, the overall fracture behaviour of the weld is dominated by the remaining fracture resistant material.

In terms of the performance of HMAS COLLINS, this means that the forging to plate welds possess an outstanding resistance to fracture under explosive loading. The investigation also confirms that the explosion bulge test is reliable and correct, and it highlights the point that structure-property investigations of weld metal must view the weld as a whole rather than infer mechanical properties on the basis of one microstructural feature.

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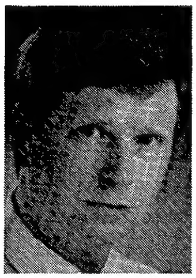

Dr. Len Davidson is a Research Scientist in the Ship Structures and Materials Division of AMRL. He received a BSc(Hons) in Physics and Geology from the University of New Brunswick, Canada, and was awarded a PhD by Monash University for research on the role of point defect chemistry in the creep of ZnS. He has worked as a geologist, a geophysicist, an electron microscopist and a consulting metallurgist. At AMRL his research areas include weld metal structure-property relationships for improved resistance to shock and hydrogen-induced cracking as well as remaining life assessment and life extension of defence platforms.

Contents

1. Introduction

MIL-E-10018-M1 (E-10018) electrodes are used to weld HY590 forgings to BIS 812 EMA plate in the pressure hull of the COLLINS class submarines. In-situ metallography of welds in COLLINS, deposited using the E-10018 electrodes, revealed extensive networks of pro-eutectoid grain boundary ferrite: a microstructural component generally thought to be deleterious to toughness (Figure 1). However, E-10018 weld metal had been previously found to possess a good Charpy impact toughness (Table 1) and had passed the demanding explosion bulge test. A metallographic inspection verified that the weld metal which passed the explosion bulge test also contained networks of pro-eutectoid grain boundary ferrite and was microstructurally and therefore mechanically representative of the E-10018 weld metal in the COLLINS pressure hull (Figure 2).

The purpose of the current investigation is to reconcile the contradictory relationship between good fracture toughness and the presence of a seemingly deleterious microstructural component in the E-10018 weld metal. In order to achieve this, the report focuses on the metallography and fractography of a multipass E-10018 weld fractured during an explosion bulge test.

Table 1. Charpy impact toughness of E-10018 weld metal. E-12018 weld metal is included in the table for comparison. (after [1]).

Electrode	Charpy V Notch -18°C (J)	-51°C (J)
E-10018	133	87
E-12018	102	66

2. Experimental method

2.1 In-situ metallography

Microstructural information was obtained from welds in COLLINS using the replication technique which follows. An angle grinder was used to remove paint from the weld and to obtain a flat region for metallographic preparation. Care was taken not to overheat the weld metal during the grinding. Fine mechanical grinding was then performed using a Struers Transpol. Successively finer grades of emery paper were used from 80 grit to 1200 grit. The region was then etched for 10 seconds with 10% nital before being mechanically polished using a polishing lap with 4-8 μm diamond paste followed by further mechanical polishing using 0-1 μm diamond paste.

The region was then etched for a few seconds using a 10% nital solution. The etchant was then rinsed off with ethanol and the etched region was inspected using a portable microscope to ensure that the metallographic preparation was successful.

Acetate film was used as the replicating medium. The acetate film was softened using a few drops of acetone and was applied to the etched structure using gentle pressure. After the acetate replicas were dry, they were removed and were affixed to glass slides using double sided tape. The replicas were gold coated to increase their reflectivity before being studied in the optical microscope.

2.2 Explosion bulge testing

The composite explosion bulge test panel studied in this report had been produced by butt welding a 50 mm thick HY590 forging to BIS 812 EMA plate. The panel had passed the explosion bulge test but was then further "tested" to destruction using additional blasts. A description of the test may be found elsewhere [2,3,4]. This test had employed the use of a brittle "crack starter" weld bead deposited along the surface of the test weld using a hardfacing electrode. A brittle crack forms in the crack starter bead during the first blast of the test and extends into the test weld during subsequent blasts. Explosion bulge tests, which employ a crack starter bead, give a good indication of a weldment's ability to arrest a crack under conditions of explosive loading. The welded panel under investigation was tested at -18°C to promote brittle fracture.

2.3 Fractography of explosion bulge panel

Initial fractography was conducted optically using a binocular microscope. Regions of interest, so identified, were investigated in detail with a scanning electron microscope (SEM).

2.4 Metallography of explosion bulge panel

Transverse metallographic sections prepared at positions along the fracture were examined optically using an inverted metallographic microscope and using an SEM. A nickel coating was applied to some specimens to improve the "edge retention" during metallographic preparation. Metallographic specimens were etched in 2% nital. Weld metal microstructures have been classified according to IIW document number IX-1533-88 [5].

3. Observations

3.1 Microstructures

The as-deposited weld metal microstructure consists of acicular ferrite† with 18% proeutectoid ferrite which forms extensive networks along prior-austenite grain boundaries (Figure 1). However, the microstructure of a multipass weldment is more complex than the as-deposited weld metal. Multipass weldments contain a number of different zones, each with its particular thermal history, microstructure and mechanical properties. In fact the as-deposited weld metal containing the pro-eutectoid grain boundary ferrite accounts for only 20% of the total multipass weld by volume.

Zones within a weldment are reheated by subsequent weld passes. Intercritically reheated zones, within the E-10018 multipass weld and in the heat affected parent metal, contain semi-continuous chains of brittle high-carbon martensite-austenite particles (Figure 4 and 3 respectively). These particles give rise to local brittle zones and have been the subject of a number of recent structure-property relationship studies [6,7,8,9,10].

3.2 Fractographic and metallographic examination of fracture path

On the convex side of the explosion bulge test panel the longitudinal fracture runs in the weld metal parallel and immediately adjacent to the fusion boundary. On the concave side of the panel the longitudinal fracture leaves the fusion boundary and cuts directly through the heart of the multipass weld, passing through both as-deposited and reheated weld metal (Figures 5 and 6). Where the fracture passed through the reheated weld metal it cut randomly across the microstructural features. In particular there was no evidence that the fracture propagated through the semi-continuous chains of brittle martensite-austenite particles in the intercritically reheated weld metal (Figure 4), nor evidence of the fracture passing through martensite-austenite particles in the intercritically reheated heat affected zone (Figure 7). In many instances the crack changed direction, following the fusion boundary around the intercritically reheated heat affected zone.

However, information gained from metallographic sections through the fracture, points to the significance of the grain boundary ferrite in the fracture process. There are a number of steps in the fracture path, shown in Figure 5, which are at a high angle to the overall fracture. These steps link regions of as-deposited weld metal where the

† Note: there is some question as to whether acicular ferrite may be positively identified using an optical microscope.

fracture has followed the columnar structure. The detail of one of these steps is shown in Figure 8.

Detailed examination of the fracture surface revealed a mixed mode of ductile failure (~85%) and quasi-cleavage(~15%) in the as-deposited weld metal. In those regions where the fracture intersected the as-deposited weld metal the fracture face is similar in morphology and dimension to the columnar structure of the as-deposited weld metal (Figure 9). A small component of the fracture in these regions is brittle intergranular, with respect to the columnar prior-austenite structure (Figure 10). The vast majority of the fracture is ductile with numerous shear walls evident. A number of features appear to be cleavage facets (Figure 11) but on closer inspection these all exhibit limited ductility (Figure 12).

4. Discussion

It has been shown above, that although the fracture is not microstructurally controlled in the reheated weld metal, grain boundary ferrite is the preferred fracture path in the as-deposited weld metal. In those regions, it is proposed that fracture occurs along the grain boundary ferrite in the stress field ahead of the advancing crack. As the crack advances, these cracks become linked by shear walls, which form large steps in the fracture seen in Figure 5.

Fractography indicates that much of the fracture of the as-deposited weld metal occurs by a ductile mechanism with small regions of low ductility fracture. The precise role of the grain boundary ferrite in this largely ductile failure is still unclear. Tweed and Knott [11] demonstrated that in a C-Mn weld containing acicular ferrite and grain boundary ferrite, strain will be localised in the grain boundary ferrite until the bulk specimen strain reaches 7%. They also noted a tendency for the fracture to preferentially follow the grain boundary ferrite but suggested that this effect "is not particularly large". It is therefore suggested here, that the fracture in the as-deposited weld metal may occur by localised plastic deformation in the grain boundary ferrite followed by localised failure in the grain boundary ferrite. However, further work would be required before the precise micromechanism of failure could be elucidated. Moreover, it is unknown whether the grain boundary ferrite is related to either the low ductility "facets" of Figure 12 or the intergranular fracture seen in Figure 10. Although the grain boundary ferrite network has a lower fracture resistance than the bulk microstructure, failure in the as-deposited weld metal has a substantial ductile component with numerous shear ledges (Figure 10). This indicates that a substantial amount of energy would be required to propagate a fracture through the as-deposited weld metal, despite the grain boundary ferrite. Moreover, a multipass weld is comprised of a number of microstructural zones and only the as-deposited weld metal contains the grain boundary ferrite. Since the as-deposited weld metal accounts for only 20% (by volume) of the multipass weld, the overall effect of the deleterious structure is greatly reduced.

The fact that as-deposited weld metal may account for less than half of a multipass weld is often overlooked in structure-property investigations of weld metal and as a result, an inordinate amount of time and effort is spent investigating as-deposited weld metal rather than investigating the weld as a whole.

Much of the fracture resistance of the weld metal will be derived from the interlocking grains of acicular ferrite seen in Figure 2. Since cleavage fracture in ferrite occurs along {100} planes, a fracture must change direction when it crosses a high angle boundary between adjacent grains of acicular ferrite. The smaller the grain size the more tortuous the fracture path and the greater the resistance to cleavage fracture [12]. The result is that an acicular ferrite microstructure is very resistant to cleavage fracture and confers good toughness to the weld.

In a comparative investigation of consumables for use in joining HY-80 plate for warship construction, it was found that the weld metal which gave the best toughness consisted of fine acicular ferrite with 5% proeutectoid grain boundary ferrite [13]. The authors indicated that in their experience, proeutectoid grain boundary ferrite appeared to be innocuous in amounts up to 3%. However, the present investigation would suggest that in some cases, proeutectoid grain boundary ferrite may be tolerated in quantities up to 18% of the as-deposited structure.

Martensite-austenite particles have been shown elsewhere to seriously reduce toughness by initiating brittle fracture [14] and by offering little resistance to an advancing crack [15]. However, the detailed examination of metallographic sections through the fracture produced no evidence that the fracture followed the semi-continuous chains of martensite-austenite particles, indicating that this mechanism has not operated to any significant extent.

5. Conclusions

From the detailed fractographic and metallographic examination of a fracture through a multipass weldment deposited using E-10018 electrodes, it is concluded that:

1. The MIL-E-10018-M1 weld metal which passed the explosion bulge test is microstructurally and therefore mechanically representative of the MIL-E-10018-M1 weld metal in the COLLINS pressure hull.

2. Although grain boundary ferrite is the preferred fracture path in the as-deposited weld metal, it does not compromise the overall toughness of the weld.

3. The very good fracture resistance of this weld metal is attributed to the interlocking grains of acicular ferrite and the relatively low volume fraction of as-deposited weld metal in the multipass weld.

4. The martensite-austenite particles in intercritically reheated zones played no role in the fracture process

6. Acknowledgments

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8. Figures

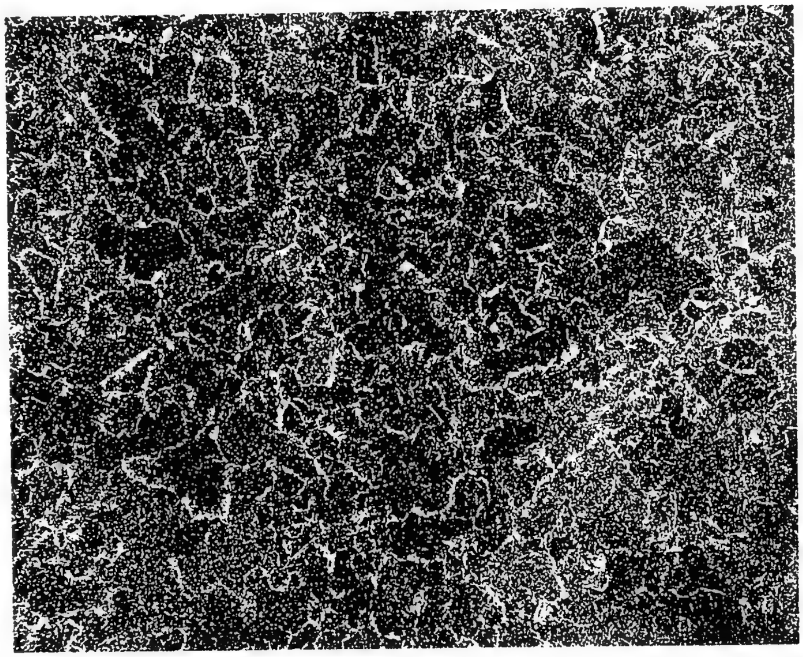

Figure 1.(a) Acetate replica of E-10018 weld metal taken from the hull of COLLINS. The metallographic "section" is parallel to the surface of the weld (ie. Perpendicular to the columnar prior-austenite grains). Note the continuous networks of pro-eutectoid grain boundary ferrite. Nital etchant. X 100

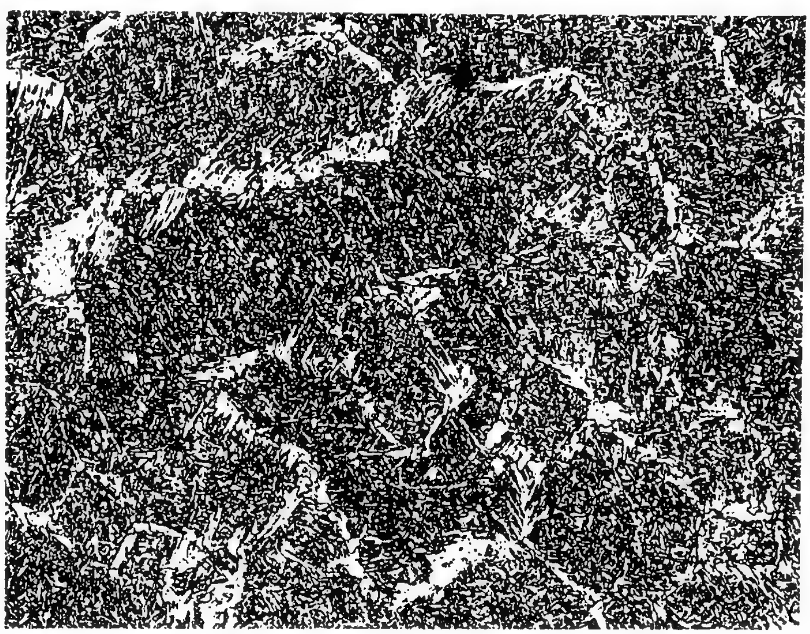

Figure 1.(b) Detail of Figure 1(a). X500

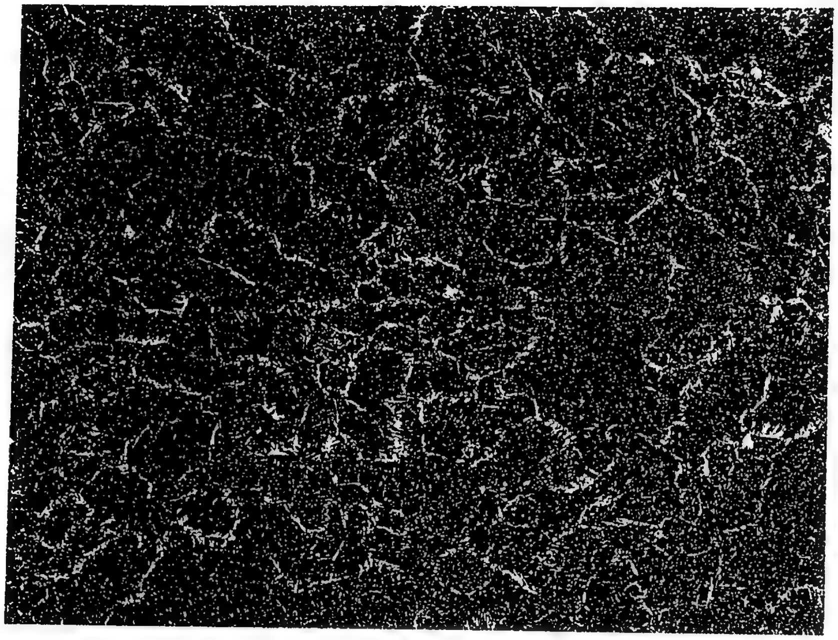

Figure 2 (a) Optical micrograph of section through E-10018 weld metal, from an explosion bulge test, cut parallel to the weld surface (ie. perpendicular to the columnar prior-austentite grains). Note the continuous networks of pro-eutectoid grain boundary ferrite. X100

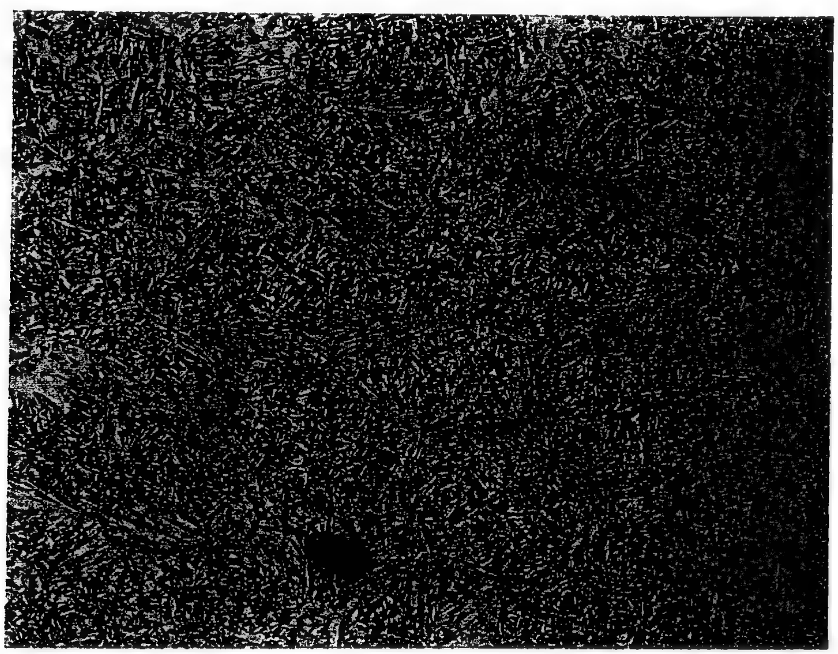

Figure 2 (b) Higher magnification of the networks of pro-eutectoid grain boundary ferrite shown in Figure 2 (a). X500

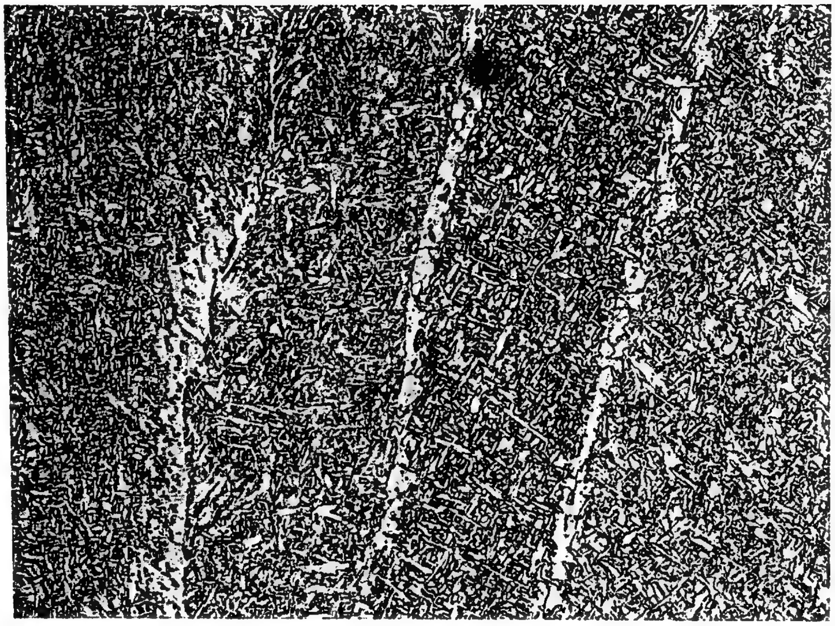

Figure 2. (c) Optical micrograph of transverse section of E-10018 weld metal from an explosion bulge plate. Note the continuous networks of pro-eutectoid grain boundary ferrite. Nital etchant. X200

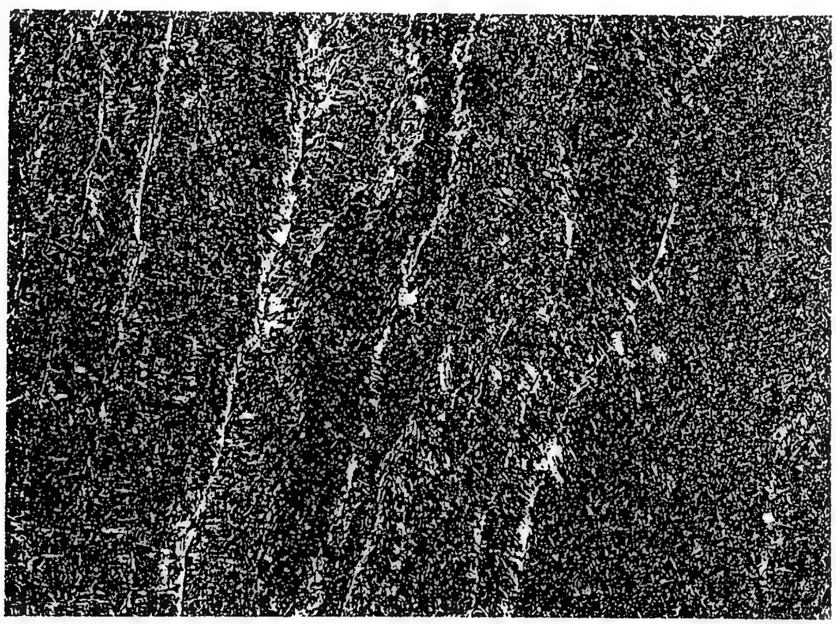

Figure 2. (d) Higher magnification of the networks of pro-eutectoid grain boundary ferrite shown in Figure 2 (c). X500

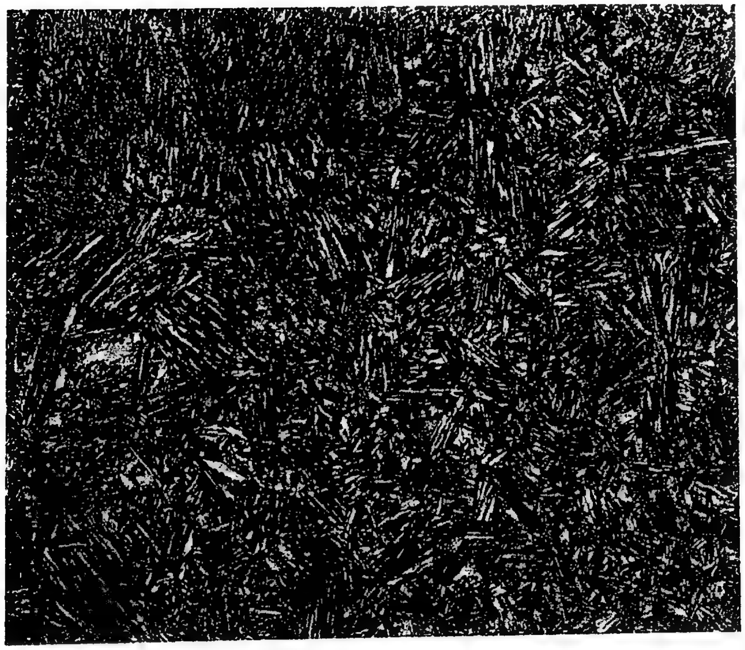

Figure 3.(a) Optical micrograph of intercritically reheated grain coarsened HAZ in BIS 812 EMA. X200

Figure 3(b) Electron micrograph of martensite-austenite particles decorating prior austenite grain boundaries. X575

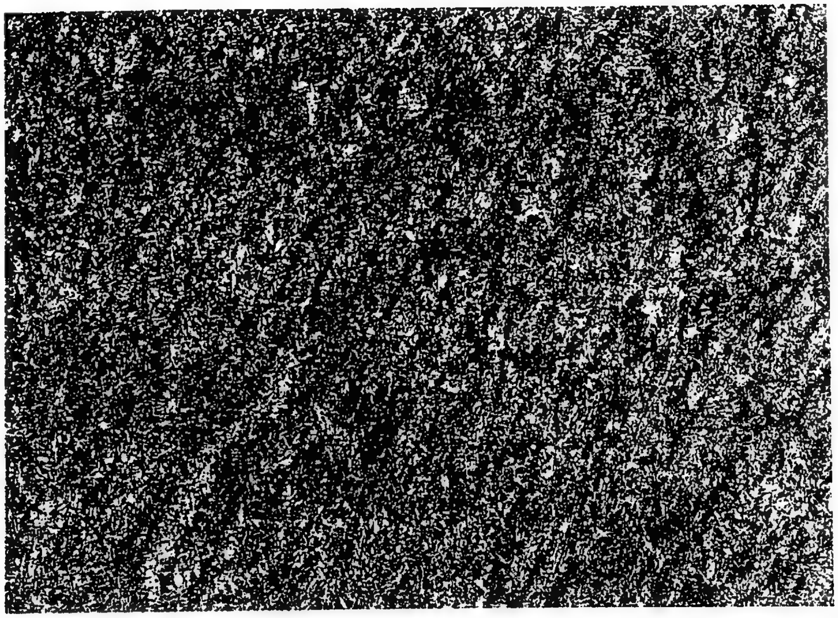

Figure 4.(a) Optical micrograph of intercritically reheated E-10018 weld metal, from the explosion bulge plate, containing chains of brittle martensite-austenite particles. X200

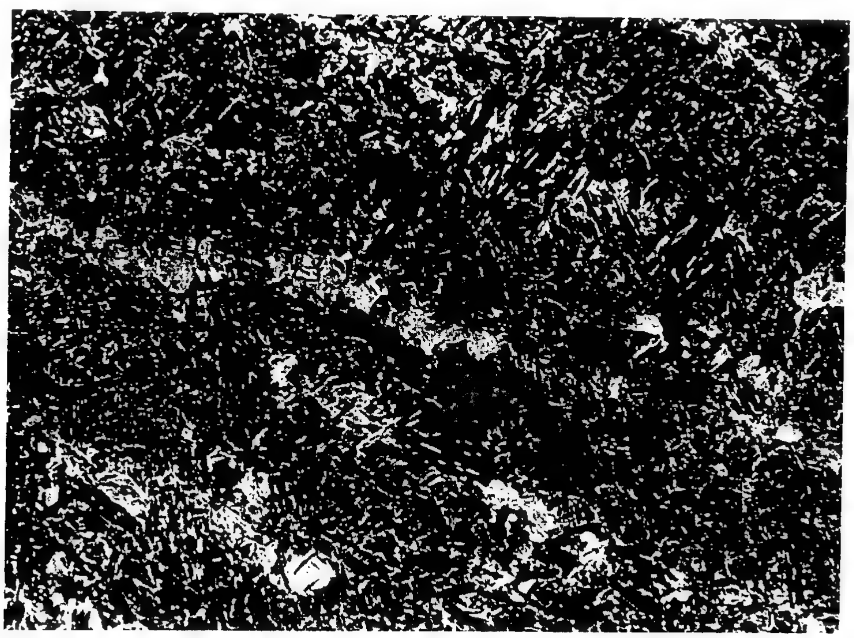

Figure 4.(b) Electron micrograph of martensite-austenite particles in E-10018 weld metal from the explosion bulge plate. X775

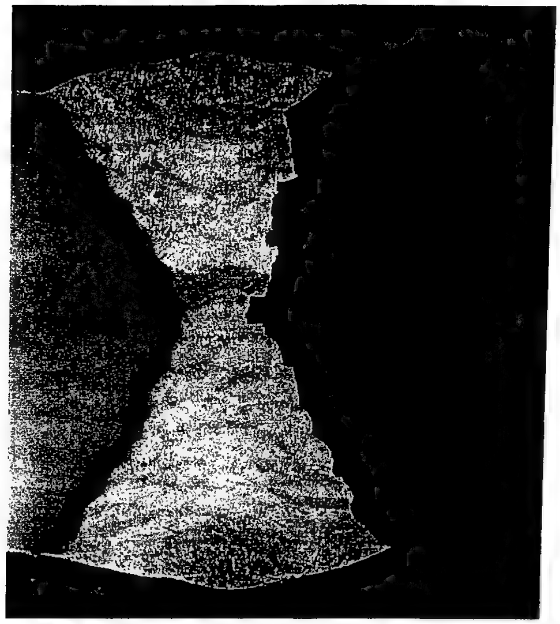

Figure 5. Transverse metallographic section through the longitudinal fracture. The tension side of the explosion bulge plate is seen at the bottom of the photo.

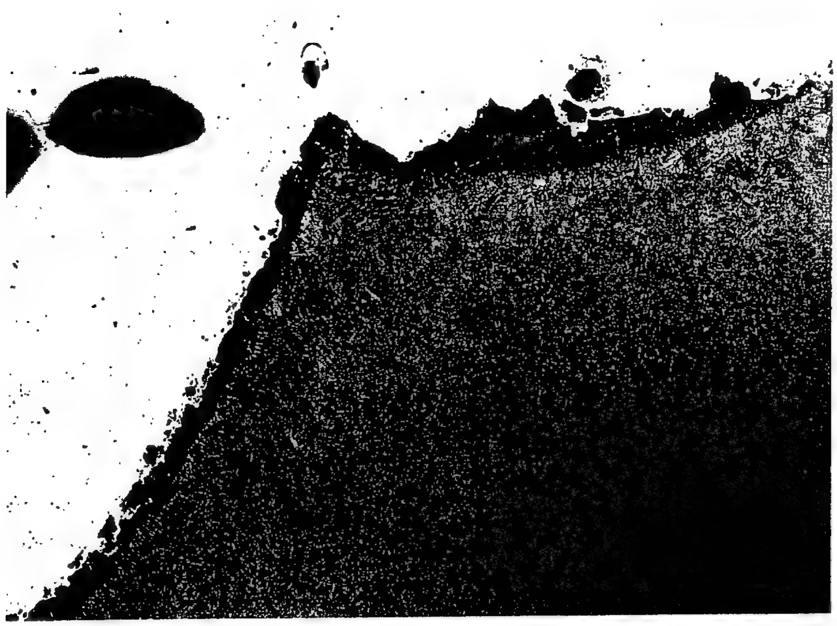

Figure 6. Optical micrograph showing the longitudinal fracture running immediately adjacent to a fusion boundary. X50

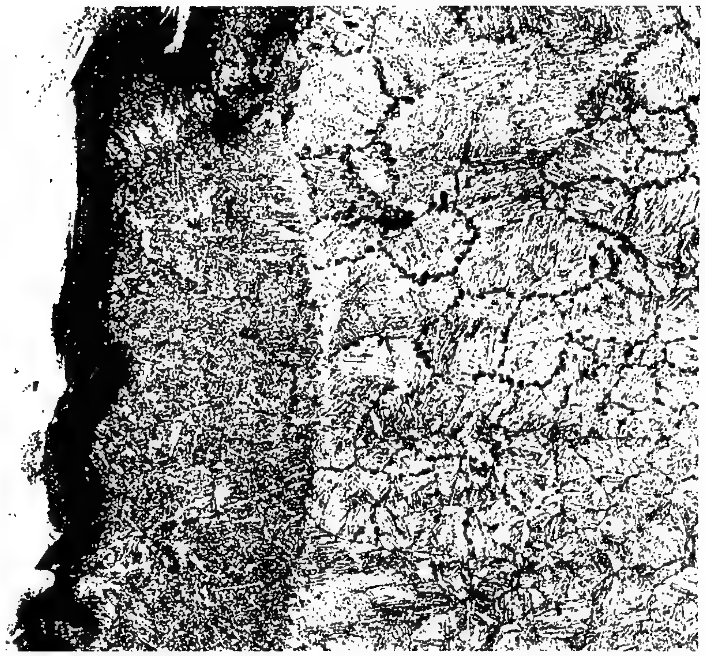

Figure 7. Optical micrograph of the fracture in the weld metal next to the fusion boundary and showing no preference for the inter-critically reheated grain coarsened HAZ. X200

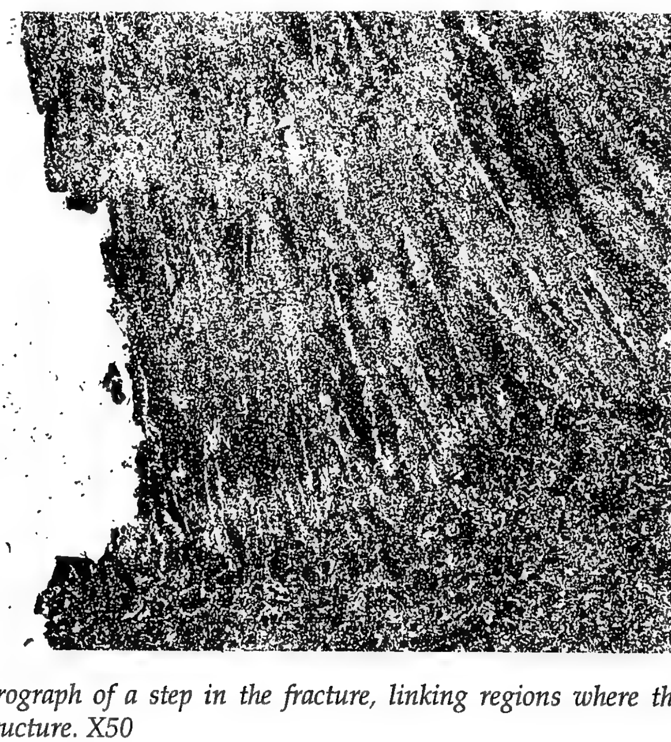

Figure 8. Optical micrograph of a step in the fracture, linking regions where the fracture follows the columnar structure. X50

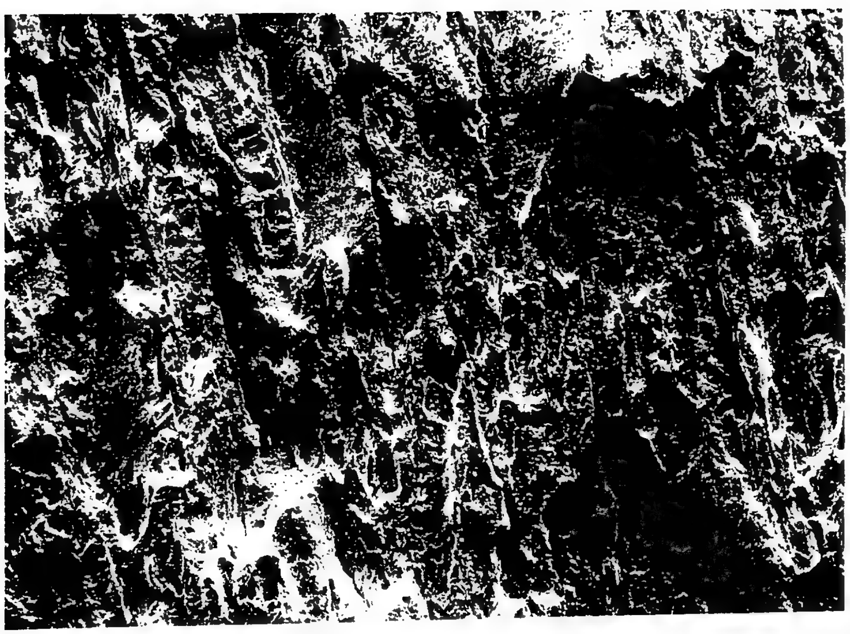

Figure 9. Electron micrograph of fracture through as-deposited weld metal. X50

Figure 10. (a) Brittle intergranular fracture along a prior-austenite grain boundary in the as deposited weld metal (indicated by the black arrow). X100

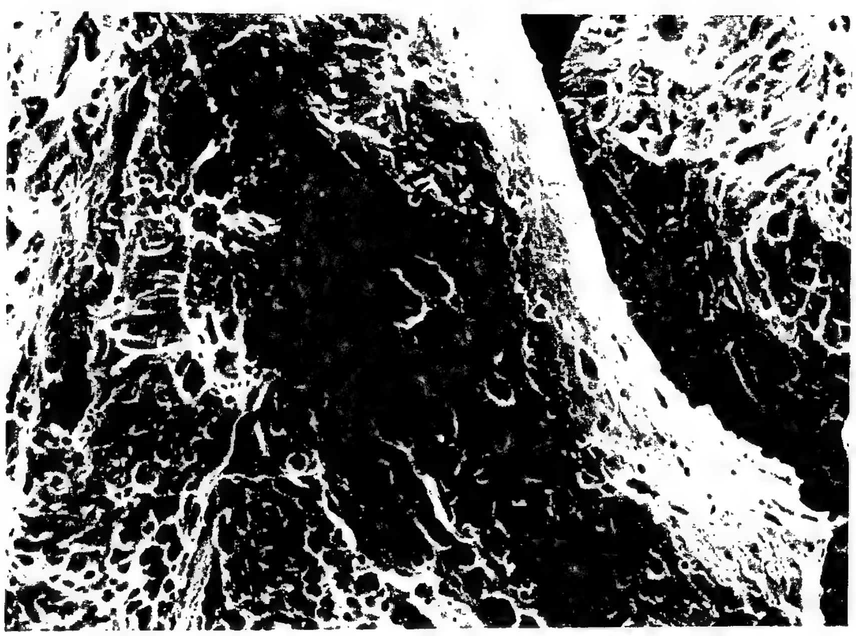

Figure 10. (b) Detail of the intergranular fracture shown in Figure 10 (a). X1000

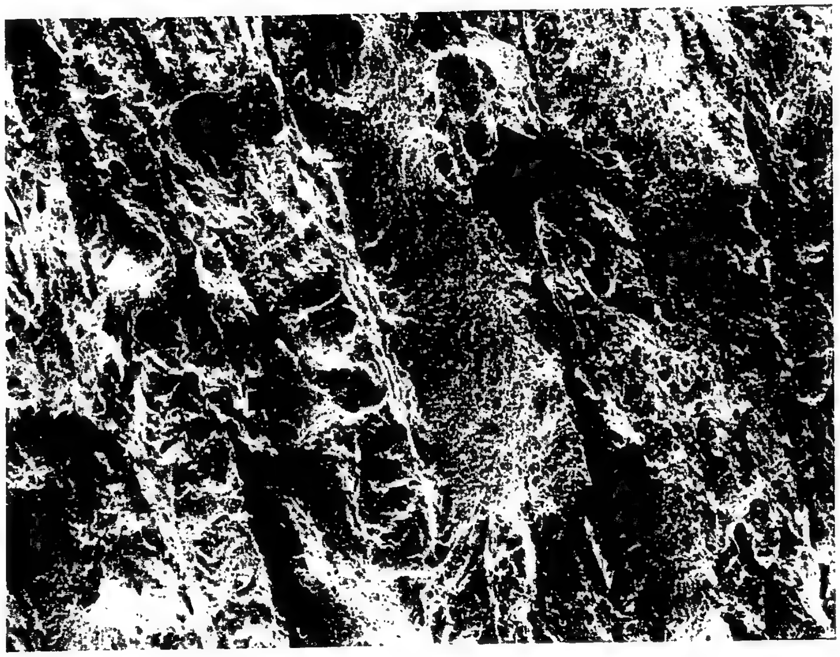

Figure 11.(a) Fracture through the as-deposited weld metal. The fracture is largely ductile, but it appears to have a number of cleavage facets (indicated by black arrows). X100

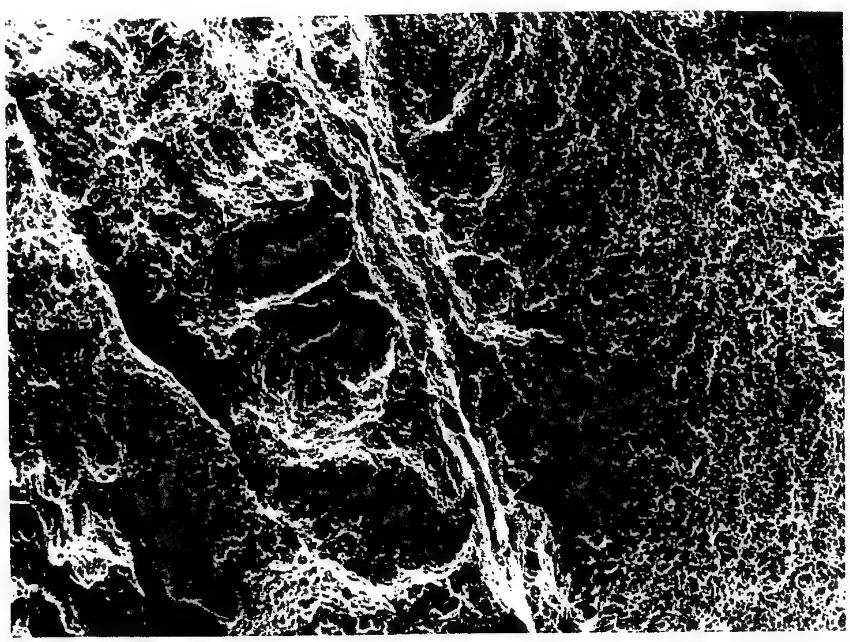

Figure 11.(b) Magnified overview of "cleavage facets". Note the brittle intergranular fracture indicated by black arrow. X280

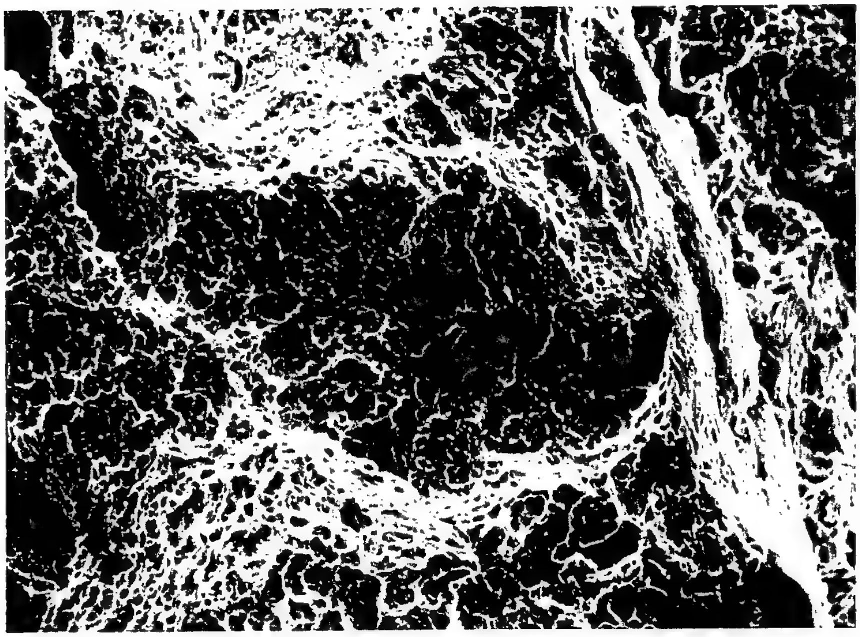

Figure 12. Detail of the fracture showing varying degrees of ductility found in the "facets" (a) Relatively large ductile component of a "faceted" region. Also note the featureless brittle intergranular fracture at the far right of the micrograph. X700

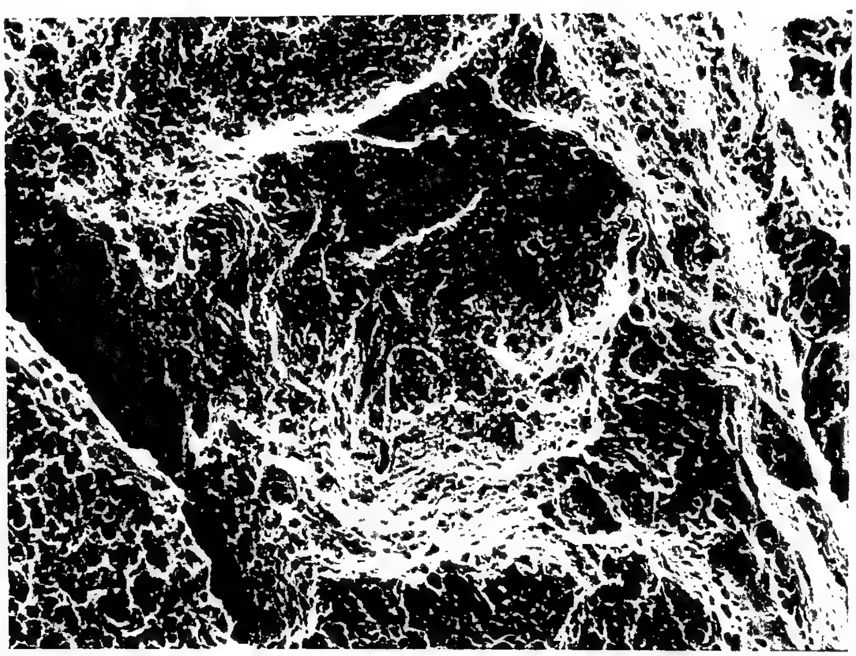

Figure 12 (b) A "faceted" region with a reduced, yet substantial, ductile component. X700

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Weld metal deposited using MIL-E-10018-M1 electrodes maintains very good fracture resistance, despite being comprised of a seemingly deleterious microstructure which includes extensive networks of pro-eutectoid grain boundary ferrite in the as-deposited weld metal and brittle martensite-austenite particles in the intercritically reheated weld metal and heat affected zone. To reconcile this contradictory structure-property relationship the report focuses on the fractography and metallography of a MIL-E-10018-M1 multipass weld, fractured during an explosion bulge test. Martensite-austenite particles identified in the intercritically reheated weld metal and heat affected zones were found to play no part in the fracture process. Pro-eutectoid grain boundary ferrite was shown to be the preferred fracture path in the as-deposited weld metal however, it does not substantially reduce the overall fracture resistance of the multipass weld metal. The very good fracture resistance of this weld metal is attributed to the